

Measurement of Air Temperature using Thermochromic Liquid Crystal Technology

An Undergraduate Honor THESIS

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Abstract

Thermochromic Liquid Crystals (TLCs) are commonly used for heat transfer measurement experiments, since TLCs react to changes in temperature by changing color, which can be recorded by a standard visual-light camera. This research will explore a novel use of TLCs by applying them to a thin filament to measure air temperature changing. Traditional methods for measuring fluid temperature, such as miniature thermocouples, can only determine the temperature at a single point or a small array of points and are not able to provide a profile of the whole cross section. Because it only requires a standard visual-light camera to record the color change and determine the temperature, this method is easily integrated with the rotating experiments that are required for determining the flow behavior in jet engines and other complicated flow geometries. The purpose of this project is to build a TLC thermal model on filaments to measure and map the air temperature change in the test section of a blowdown wind tunnel. This study can help to provide a method for measuring the fluid temperature profile across a full passage of a wind tunnel, providing more accurate and detailed boundary conditions for experiments.

Keywords: Liquid-crystal thermography; Calibration; Hue; Temperature measurement

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Chapter 1: Introduction

1.1 Motivation

Thermochromic Liquid Crystals (TLCs) are commonly used for heat transfer measurement experiments, since TLCs react to changes in temperature by changing color, which can be recorded by a standard visual-light camera [3-4]. Most recent experiment did the experiment on the metal plates and the previous experiments all got nice and reliable results. But doing the experiments on the metal plates would cause vertical conduction so that the measurement would not be precise and always have system error in it. To measure or map a temperature field on a test article, the researcher needs to airbrush the black ink on to the article and then spray the TLC to cover it [4-5, 11]. A camera is set up to catch the change in RGB color. The camera is connected to a computer with a program converting the RGB¹ value into HSV² value. Using Matlab image tools to determine the RGB values of the points selected in the figures which taken by the camera. Also by Matlab, convert RGB color model to HSV color model, so the relationship between the HSV and the temperature is determined.

All the experiments will be held in the Gas Turbine Laboratory. Successful execution of the experiment requires determination of the source of the TLC, the material to be used for

¹ RGB: an additive color model in which red, green, and blue light are added together in various ways to reproduce a broad array of colors.

² HSV: cylindrical-coordinate representations of points in an RGB color model.

the test article, and the type of the camera and light source required. Two companies (QATS Inc. and Hallcrest) provide TLC for heat transfer measurement and mapping experiments. After comparing temperature detecting range, bandwidth and some other features of the TLC kits they provide and factoring in budget considerations, Hallcrest (Figure 1) was selected to be the main TLC supplier for this research project [4].



Figure 1 Black backing painting and ThermoChromic Liquid Crystal experiment kit [4]

To successfully determine the mathematical relationship between hue and temperature by TLCs, two calibration experiments will be held. Both calibration experiments will be tested in an vacuum oven, the first calibration step is to make sure TLCs which applied on the test articles still react when the surrounding temperature changes. Also this step can ensure the Gopro camera and the Matlab code performs well. The second calibration will be used to build the accurate relationship between hue and temperature. So the temperature change can be visually observed by the color changes reacted by TLC through the camera. The numerical value of temperature change over the whole process can be determined by program in the computer.

1.2 Objective

The purpose of this project is determined to the air temperature change in the wind tunnel cross-section.

- i. Research on the characteristics of different types of metals and find the most appropriate materials for the experiment
- ii. Develop and prove a technique to measure air temperature using liquid crystals applied to a thin filaments
- iii. Get familiar with Matlab Image Tools in order to analyze the temperature changes over time intervals
- iv. Build an relationship between hue changes and air temperature change

1.3 Overview of the thesis

This thesis has 5 chapters. Chapter 2 introduces background. Chapter 3 explains the methodologies. Chapter 4 includes results, data analysis and discussions. Chapter 5 summarizes the conclusions and provides recommendations for future works.

Chapter 2: Background and Literature Review

TLC technology is commonly used in heat transfer measurements and mapping experiments since it will react only corresponding to changes in temperature in its active range. Also the color change can be quantitatively measured associated with a measurable scalar-- hue angle [5].

Basically, the incoming light waves reflect off nearby crystals and add together by interference and this is the reason that causes the light reflection (Figure 2) [11]. The color of the reflected light depends in a very precise way on how closely the crystals are together. Heating up or cooling down liquid crystals will change the spacing between them, altering the amount of interference and changing the color of the reflected light from black, through red and all the colors of the spectrum to violet and back to black again. In a nutshell, the liquid crystals look a different color depending on what temperature they are because changes in temperature make them move closer together or further apart (depending on the material). The color changing associate with the spectrum shows below (Figure 3), as the temperature higher the color liquid crystals will reflect more blue color while the lower temperature will reflect redder.

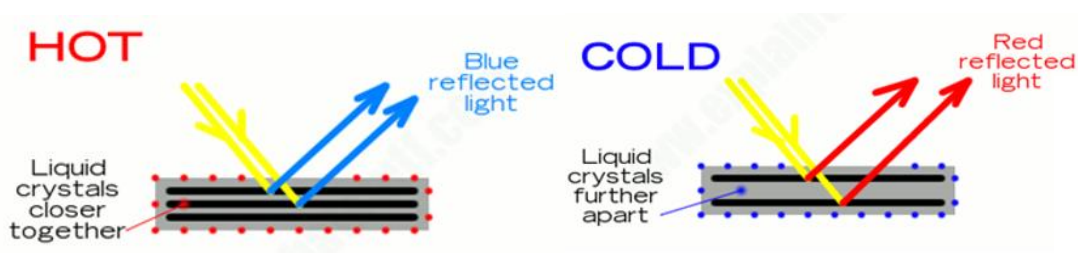


Figure 2 the TLC color changing principle

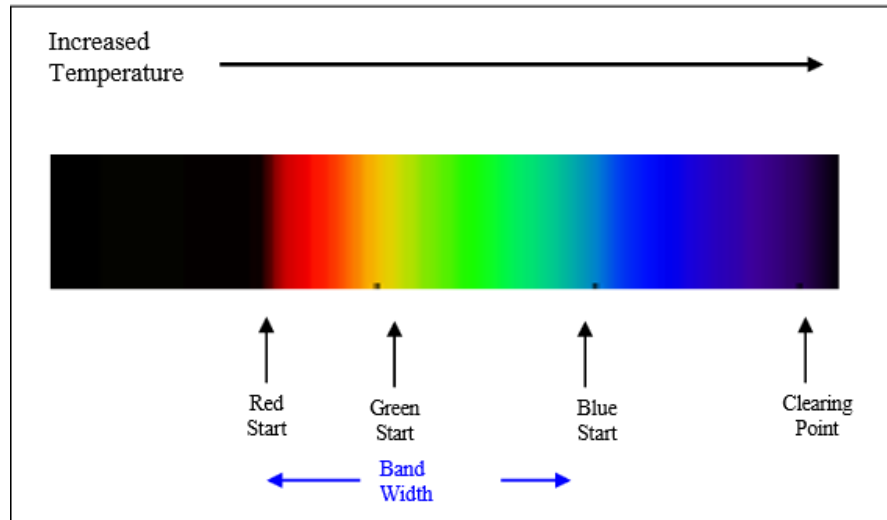


Figure 3 Typical color play of Thermochromic liquid crystals [2]

In the Gas Turbine Laboratory, there is a blowdown wind tunnel (Figure 4 and Figure 5) built up to explore new experimental or data processing techniques as well as for comparison to computational predictions[13]. In order to measure the temperature changing in the test section of the blowdown wind tunnel, the researchers usually use thermocouples (Figure 6) to determine the temperature [11]. Due to different materials, approximately thermocouples will have rapid responses at a large temperature range from -200°C to 2500°C . The thermocouples are robust when processing and because thermocouples require no excitation power, they are not prone to self-heating and intrinsically safe. However, the most important thing is that thermocouples can only determine temperature where the measurement junction is at rather than the temperature profile over the whole cross section. What's more, it is hard to design the rake to fit the thermocouples to measure the boundary layer temperature.

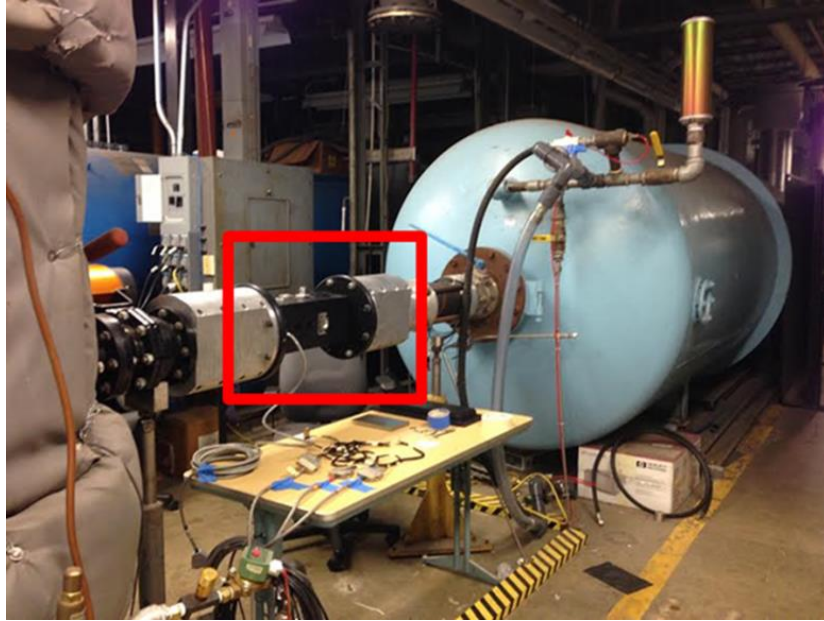


Figure 4 blowdown wind tunnel in the GTL (red box highlights the test section)



Figure 5 the blowdown wind tunnel test section

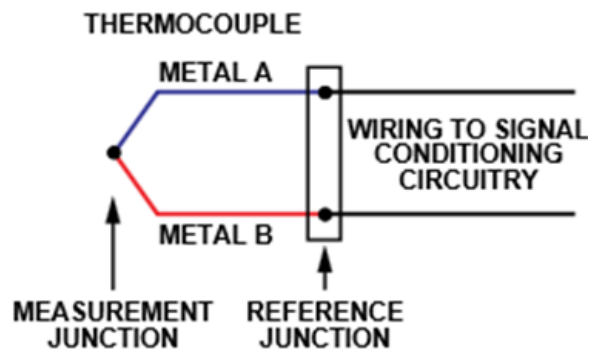


Figure 6 Sample Thermocouple

In Gas Turbine Laboratory, researchers usually use several thermocouples to measure temperature in the cross section of the blowdown wind tunnel. Figure 7 below shows a sample thermocouple rake, whose structure is complicated and due to the space limitation, eleven thermocouples are the most to fit in. But the more measurements the more accurate temperature measurements are. Besides, thermocouples can only tell temperature at one point or small array of points that they are attached to. Therefore building a thermal model using TLC technology to measure the temperature can be useful.



Figure 7 Thermocouple Rake with 11 thermocouples on it

A group of German engineers have done a heat transfer measurement experiment by TLCs [6]. In order to do this calibration experiment, they used a digital camera to capture the color signals from TLC-coated surface and aligned them with measured temperature

distribution. The experiment setup is shown in the Figure 8. The TLCs were applied on an isolated copper plate and constantly heated it up. They had the photos taken at same intervals and data analyzed. And the results show below (Figure 9).

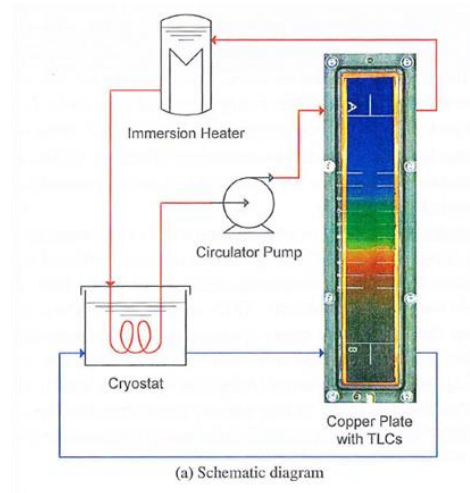


Figure 8 Experiment setup for the previous calibration experiment [6]

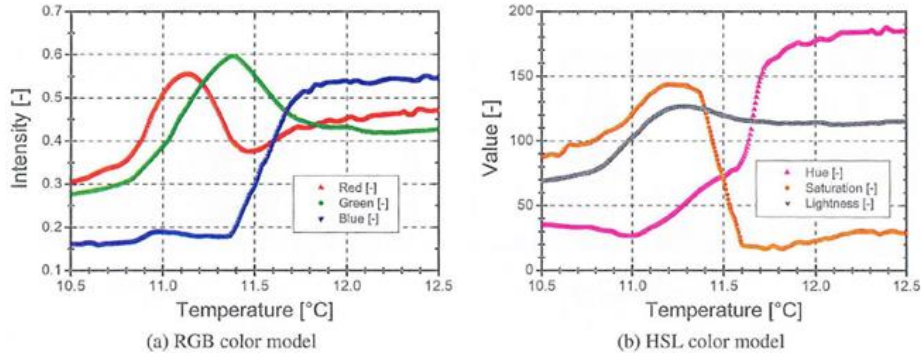


Figure 9 Experiment results between temperature and color[6]

The left plot shows the temperature changes and the color change in RGB model, the right plot shows temperature change and the color change in HSL model. It is clear that hue value goes up when the temperature raises up, also it shows the largest detectable range when the temperature changes. So it is reliable and useful to use hue as the measurement scalar to do the experiments.

Chapter 3 Methodology

This chapter introduces the materials used and methodologies adopted for the research.

The research project has three experiments processed. Two vacuum oven calibration experiments and one reaction time measurement experiment.

In the all the experiments, the researcher will use Black Backing Paint and Chiral Nematic Sprayable Liquid Crystal [5] provided by Hallcrest co. and Gopro Hero4 camera to record the process.

3.1 Vacuum oven calibration experiment 1

3.1.1 Pre-experiment preparation

3.1.1.1 Test piece design

The test piece used an already built aluminum piece, warped by the fishing lines. The fishing line diameter is 0.015 m and each two lines are 1/8 inch apart. The design is shown below (Figure 10).



Figure 10 Test piece 1

3.1.1.2 Painting TLC

3.1.1.2.1 Cleaning

In order to clean wires thoroughly to remove all dirt, grease, fingerprints, etc. the researcher used acetone, petroleum ether and some other common organic solvents to clean the surfaces absolutely. Then dried the whole piece completely before proceeding forward.

3.1.1.2.2 Coat the wires black.

Since the wire was white, the TLC cannot be applied directly. This kind of Black paints would air dry in 20-45 minutes when sprayed through a good quality compressed gas sprayer. It is not a good way to apply the black paint by brush since uneven coatings affect the thermal response properties of the TLC. The black coating must be completely dry before applying the TLC coating.

3.1.1.2.3 Apply the TLC coating

Since the TLC slurry may separate to some extent on storage, it should be mixed thoroughly before use [5]. Temperatures of 20 °C are required for best results during the painting, drying and storing process. Applying TLC followed following procedure:

- i. Spray the TLC coating through airbrush (15-20cm) above the prepared surface
- ii. Air brush pressure should be approximately 20 psi/1.41 kgcm²/1.3 bar
- iii. Drying times at 20-25 °C are approximately 30-45 minutes, the exact time is depending on coating thickness. This process can be accelerated by gently blowing warm air onto the TLC coating.

- iv. The surface texture can be altered by the thickness of coating. Thin coats are matt and slightly rough while thick coats are giving a smoother gloss finishes.
- v. Coating thickness and surface texture will affect the brightness and shade of the color produced, and may also affect the temperatures at which each color appears. Generally, the thicker the coat the quicker response. But too thick a coating results in the normally bright colors appearing milky, more noticeably at the red end of the spectrum.

3.1.1.2.4 Cleaning up

The TLC coating can be removed by hot, soapy water or acetone.

3.1.1.2.5 Storage

Ideally, all TLC coatings should be stored in a refrigerator at 5-10 °C but must not be frozen to lower the materials quality. They should be warmed up to room temperature (20-30 °C) before use. Surfaces coated with TLC coatings should be stored out of UV light, and in a solvent free environment. Also, no stress should be applied to the coated surface. If stored correctly, microencapsulated TLC coatings have a useful shelf life of at least 6 months.

3.1.1.3 Vacuum oven preparation

Put the TLC-on test piece inside the vacuum oven and placed the camera right in front of the window. Covered the whole oven by the blanket to avoid the outside light causing reflection (Figure 11).

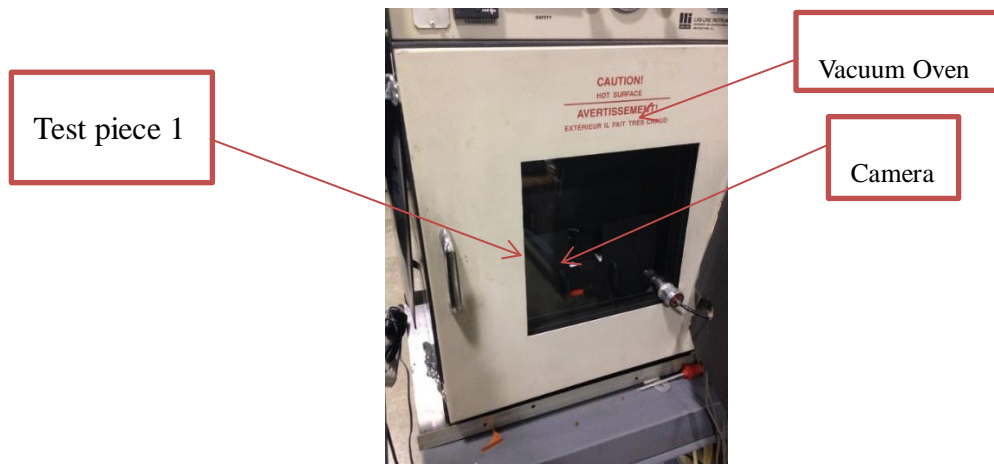


Figure 11 Calibration Experiment I

3.1.2 Experiment procedure

Started the vacuum oven at temperature 25°C (77°F) and continued heating up it. At the same time, turned on the GoPro camera to start recording. Checked with the App on the phone at the same time to make sure the process go well.

3.1.3 Post-calibration process

Exported the video from the camera and used Matlab to pick points on the wires for analysis on hue changing over time period [8].

3.2 Vacuum oven calibration 2

3.2.1 Pre-experiment preparation

3.2.1.1 Test piece preparation

Since this experiment was to measure the temperature in the test section, so the wire rake should be fit into the window in the wind tunnel (Figure 12, also see the window drawing and

test piece design drawing in the Appendix A for Figure A- 1 and Figure A- 2). This experiment used the same fishing line which tested in before to cross the holes on the rake to make a loop and tightened. Then used the same painting strategy to paint the fishing lines with TLC.



Figure 12 Test piece 2

3.2.1.2 Vacuum oven set up

After the first calibration, the researcher improved the experiment setup. Used black paper to cover the window except a square hole for camera. Set the camera right in front of the square hole to take pictures every 30 seconds. The LEDs attached to window worked as the light source for camera to record. The Resistance Temperature Detector (RTD)³ was set inside the oven to measure the air temperature (Figure 13, Figure 14, Figure 15, Figure 16). Before starting the experiment inside the vacuum oven, make the temperature inside oven at 93°F (33.5°C). After putting the test piece into the oven,

³ Resistance Temperature Detector: operate through the Callendar–Van Dusen equation to describe the relationship between resistance (R) and temperature (t) [13].

covered all the inside of oven by the black paper to avoid the reflection from background.

Last thing is to use the blanket to cover the whole oven.

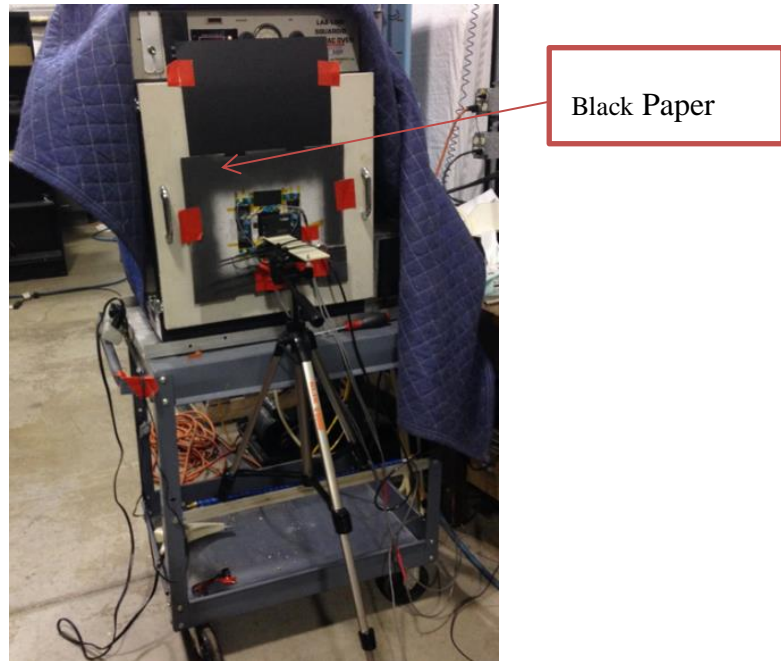


Figure 13 Calibration Experiment2 setup-1

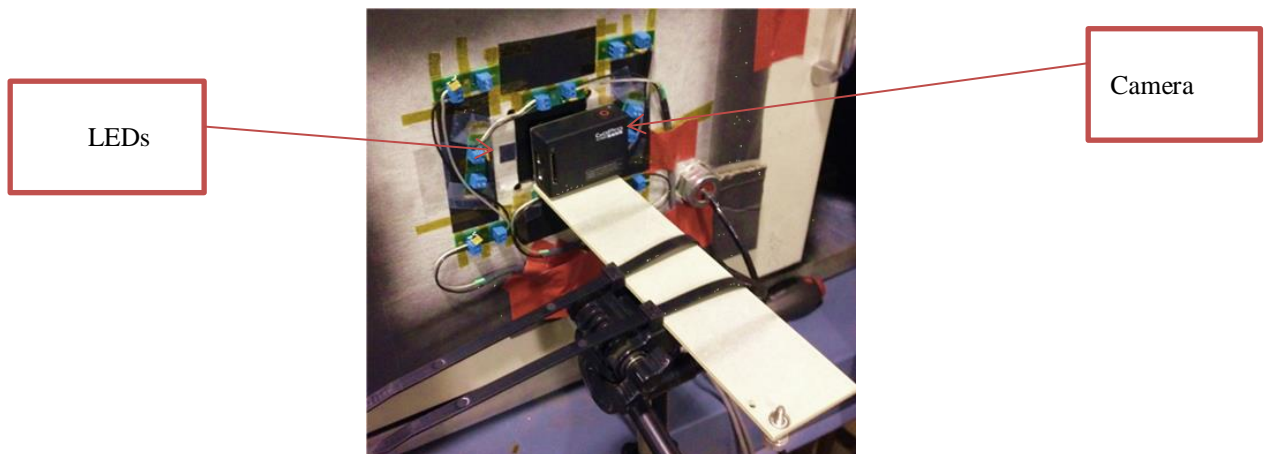
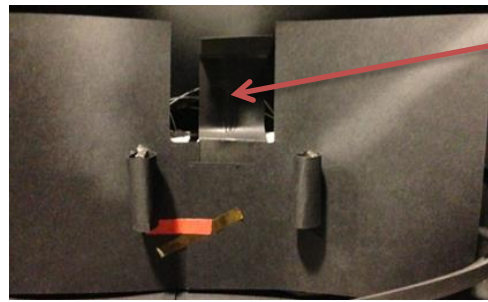
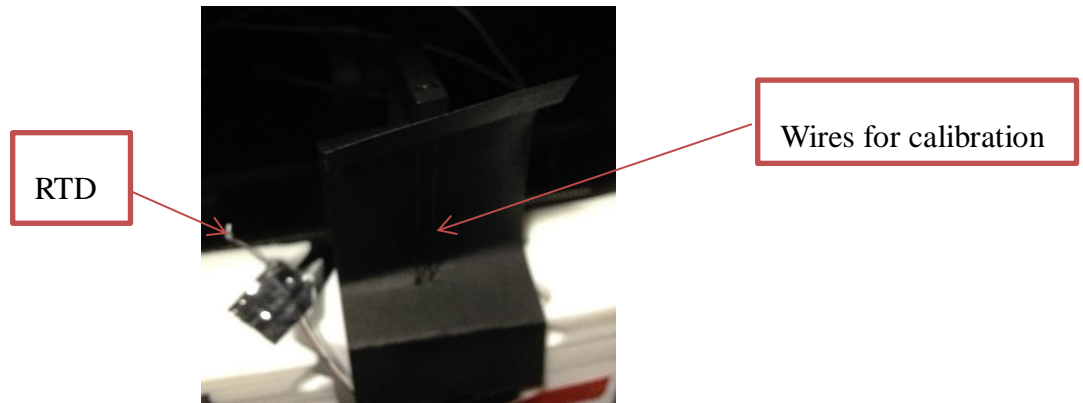


Figure 14 Calibration Experiment2 setup-2



Calibration wires

Figure 15 Calibration Experiment2 setup-3



RTD

Wires for calibration

Figure 16 Calibration Experiment 2 setup-4

3.2.2 Experiment procedure

Started the vacuum oven at temperature 33.5°C (93°F) and continued cooling down. At the same time, took photos every 30 seconds via Gopro camera. Checked with the App on the phone constantly to make sure the process go well. In the meanwhile, ran the LabVIEW program to collect the data from RTD.

3.2.3 Post-calibration process

Exported the result from the data file that collected by the RTD and converted the

resistance change into the temperature change via the Callendar–Van Dusen equation ⁴[13].

Also processed the images that taken through the experiment and extrude the hue value on wires from those images. With the help of Mr. Timothy Lawler's help, the relationship between hue and temperature has been demonstrated.

3.3 Reaction time measurement time

3.3.1 Pre-experiment procedure

3.3.1.1 Experiment set up

This experiment used the painted test piece that used in calibration experiment 2. Set up the experiment as shown in Figure 17 and Figure 18. The main structure was made of cardboard and LEDs inside the board worked as the light source for video capturing. Inside the structure, the cardboard was painted by black painting. Placed the test piece and camera in the position where shown in the Figure 17 and Figure 18. Used the heat gun as the heat source for reaction time measurement, the heating up air temperature was about is 30°C.

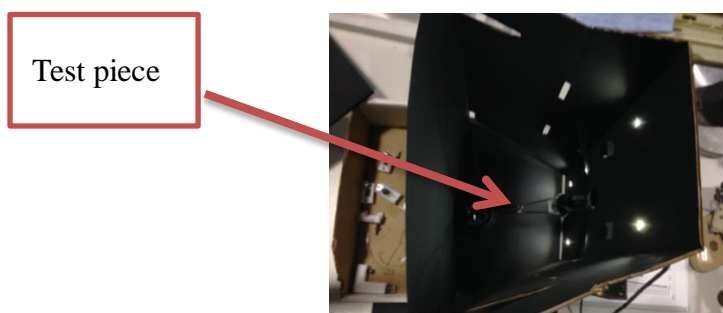


Figure 17 Experiment for reaction time measurement-top view

⁴ Callendar–Van Dusen equation: is an equation that describes the relationship between resistance (R) and temperature (t) of platinum resistance thermometers (RTD) [13].



Figure 18 Experiment for reaction time measurement-side view

3.3.2 Experiment procedure

After setting up the experiment like the figures above, covered the top and back use black paper to exclude the light reflection. Turned on the camera to record, then put the heat gun through the side hole to blow constant air onto the wires for measuring heating up time. (The air blowing direction is indicated in the Figure 18 Experiment for reaction time measurement-side view Figure 18). After about 10 seconds, removed the air gun to measure the cool down time.

3.3.3 Post-experiment procedure

Since already got the mathematical relationship between hue and temperature. After running the experiment for 6 runs, extruding the hue value changes from each videos. The hue changes can easily be seen on the plot of hue vs. time, in that way, the reaction time can be determined. Like the sample result below (Figure 19), the starting heating time to the point that hue does not change, (from red point to the yellow point) that time region can be treated

as the heating up reaction time. Similarly, the cooling down time can be measured.

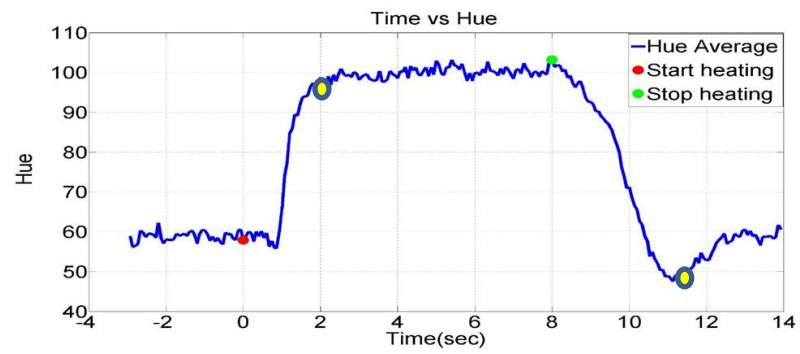


Figure 19 Sample result for reaction time measurement

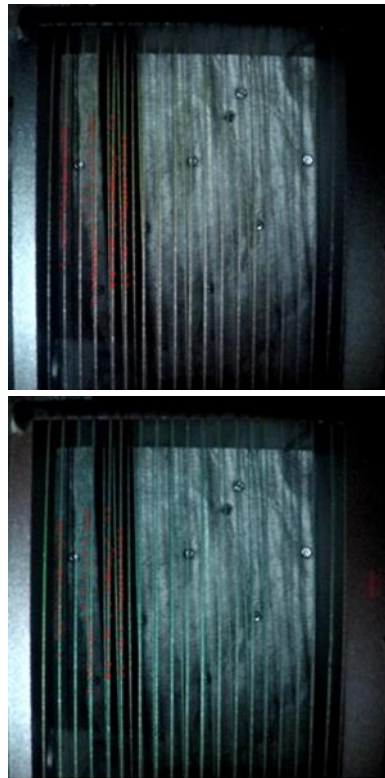
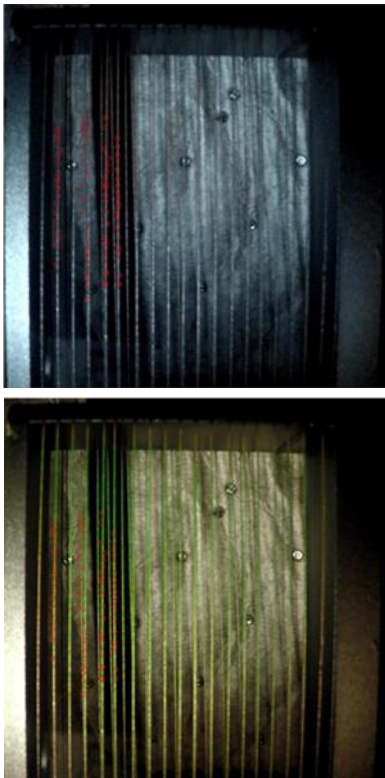
Chapter 4 Results and Discussion

This chapter will describe the results from all the experiments as introduced above and the results will be analyzed by the post-experiment procedure described above.

4.1 Calibration experiment 1

4.1.1 Calibration experiment 1 image results

Those images below (Figure 20) were from the video recorded for calibration 1. The video length was 709 seconds and there were 21000 frames stored in Matlab. Every 70th frame was processed, so there were a total 300 images used for extracting hue value. 80 points on the filaments were selected (as shown in the images Figure 21) and they were the same location in all 300 images.



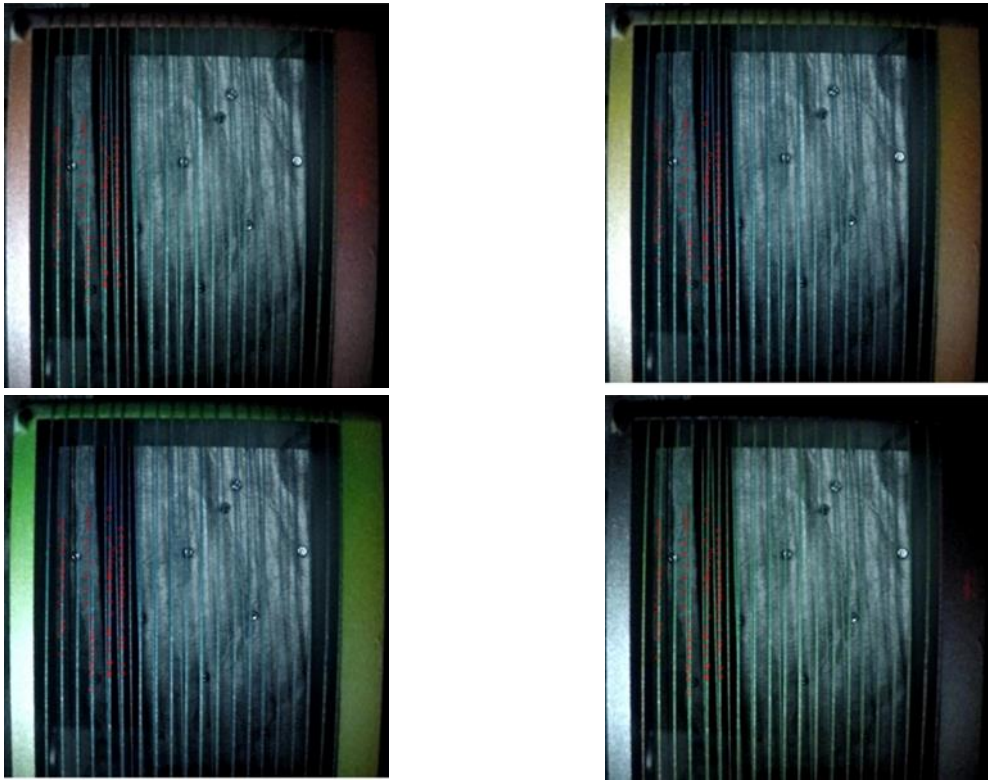


Figure 20 Calibration Experiment 1 Results for images every 100 seconds



Figure 21 Calibration Experiment 1 results for selecting points

4.1.2 Data extruded from calibration 1

Use the Matlab plot to show the hue value changing over time. (Figure 22) The green curve represents the maximum values among the eighty points over the 300 images and the red one stands for the minimum values among the eighty points over 300 images. The most focused one is the blue curve that is the average hue value of the eighty points of the 300 images.

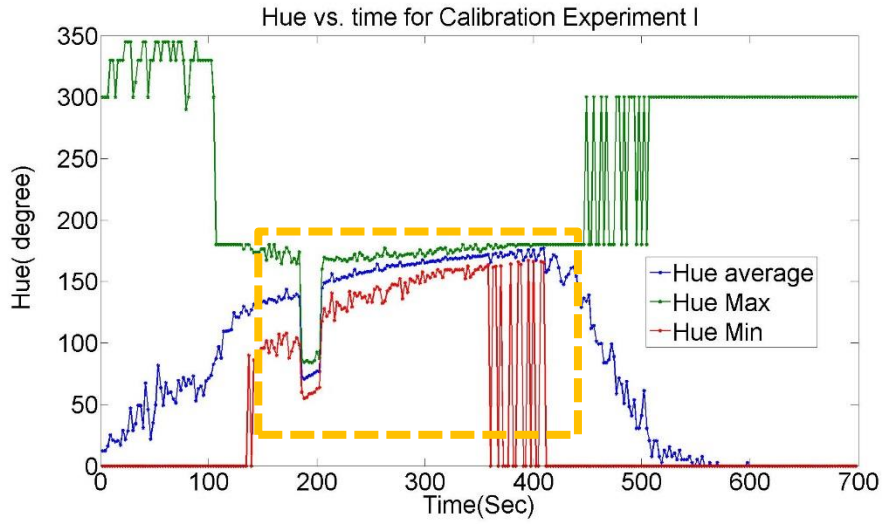


Figure 22 Calibration Experiment 1 Data Analysis

4.1.3 RGB and HSV Conversion

To convert from RGB to HSB use [2]:

The R, G, B values are divided by 255 to change the range.

$$R' = \frac{R}{255} \quad (1)$$

$$G' = \frac{G}{255} \quad (2)$$

$$B' = \frac{B}{255} \quad (3)$$

$$C_{max} = \max(R', G', B') \quad (4)$$

$$C_{min} = \min(R', G', B') \quad (5)$$

$$\Delta = C_{max} - C_{min} \quad (6)$$

Hue calculation:

$$H = \begin{cases} 60^\circ \times \left(\frac{G' - B'}{\Delta} \bmod 6 \right), C_{max} = R' \\ 60^\circ \times \left(\frac{B' - R'}{\Delta} + 2 \right), C_{max} = G' \\ 60^\circ \times \left(\frac{R' - G'}{\Delta} + 4 \right), C_{max} = B' \end{cases} \quad (7)$$

Saturation calculation:

$$S = \begin{cases} 0, C_{max} = 0 \\ \frac{\Delta}{C_{max}}, C_{min} \neq 0 \end{cases} \quad (8)$$

$$\text{Value calculation: } V = C_{max} \quad (9)$$

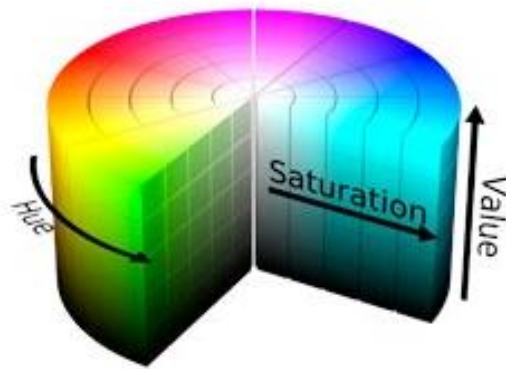


Figure 23 HSV color model visualization [1]

Where, Hue is an angle from 0 degree to 360 degrees; Saturation and Value range from 0 to 100% [1].

4.1.4 Discussion

In the Figure 22 the region that time from 120 to 170 seconds and hue from 80 to 160 (the region is indicated in the figure above) that goes for a reliable trend. In the region indicated above shows that maximum, minimum and average value all show the trend that the as the temperature raised, the hue increases.

For the time period outside the highlighted region, the average hue trend is not so clear, that maybe caused by the points picking. Eighty points that picked have various hue values. For example, the region that time less than 120 seconds, majority of the hue might be close to zero and minority might be close to 300. So when doing the data analysis, in order to get a reliable results, the researcher excluded the points that hue value is 300 or 0 when computed the average hue value.

The sudden drop at about 200 second is because that environment lightness changing suddenly so that the video hue changed a lot, which caused the drop in the figure above.

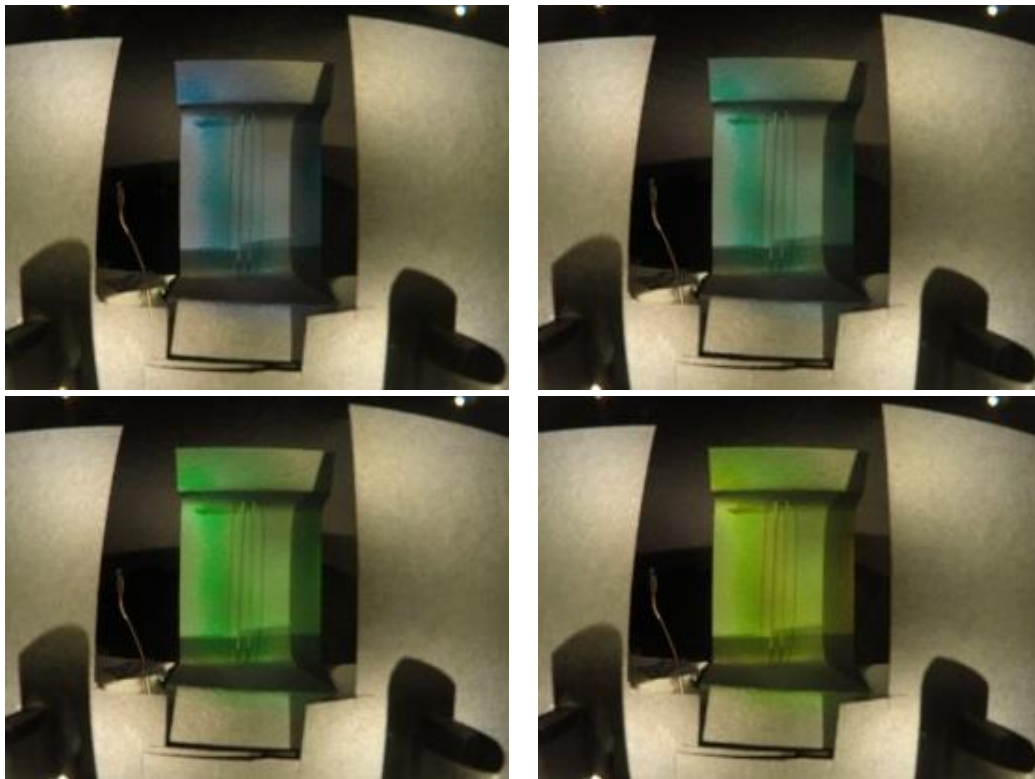
This results shows that the TLC can react color on the small surfaces like the 0.015 meter diameter fishing line, and the color changing still works as the changing principle that the temperature increases the hue increase. Besides, the Gopro camera can record clearly enough for data analysis.

4.2 Calibration experiment 2

4.2.1 Images from calibration 2

Below are the photos from the calibration experiment 2 to show the wire color changing over the whole cooling down process(Figure 24).It is clear that as the temperature decreases, the color changing from blue, green, yellow to red. It follows the typical color changing principal as the spectrum (Figure 3) introduced before.

Due to the directions of the light sources, there are four lines shown on each picture. The middle two lines are the calibration wires while the side ones are the shadows. Since the piece paper behind the wires were also painted by TLC, the color changes are easier to be observed. But the color changing on the wires also can be viewed from the images.



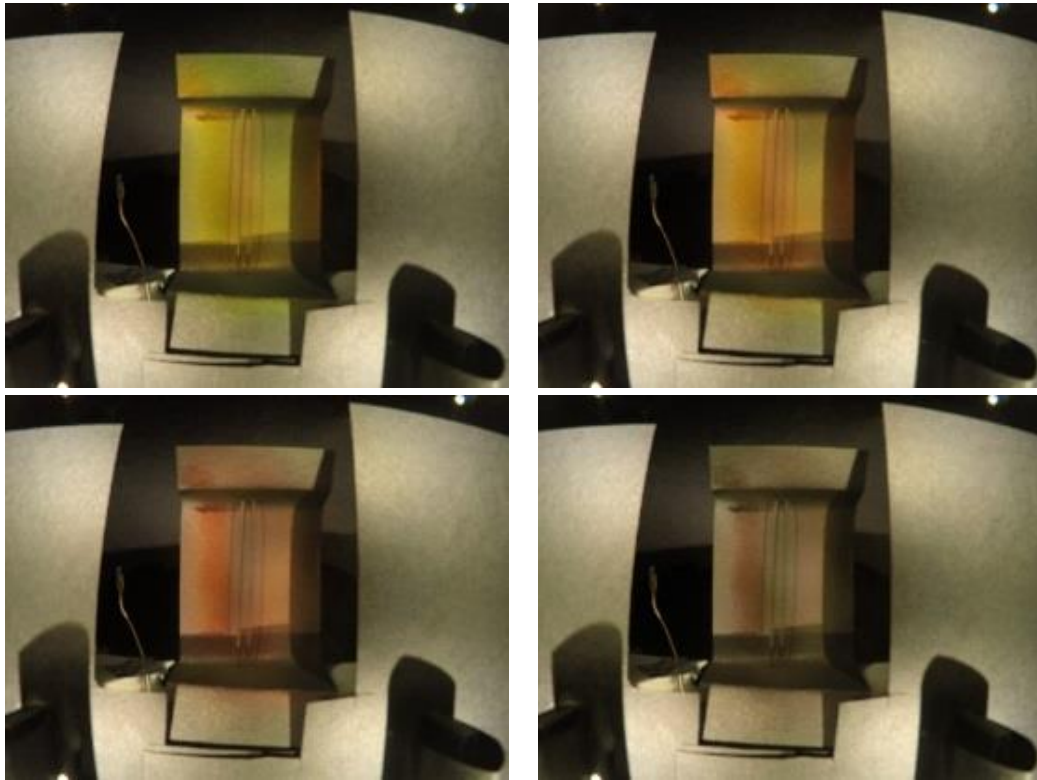


Figure 24 Calibration Experiment 2 results

4.2.2 Data extruded from calibration 2

Figure 25 and Figure 26 shown below represent the relationship between temperature and color. Their behaviors are similar with the behavior on the large metal plates (Figure 9). In the same way, the researcher focused on the relationship between temperature and hue. Figure 27 below shows the relationship between hue and temperature over all the time while Figure 29 shows relationship and 3rd order polynomial fitting in the interested region. The temperature was measured and recorded by the RTD sensor and the hue values were extruded through the images taken through processing the calibration experiment 2. The overall trend over the whole process shows that when a bigger hue value represents a higher temperature.

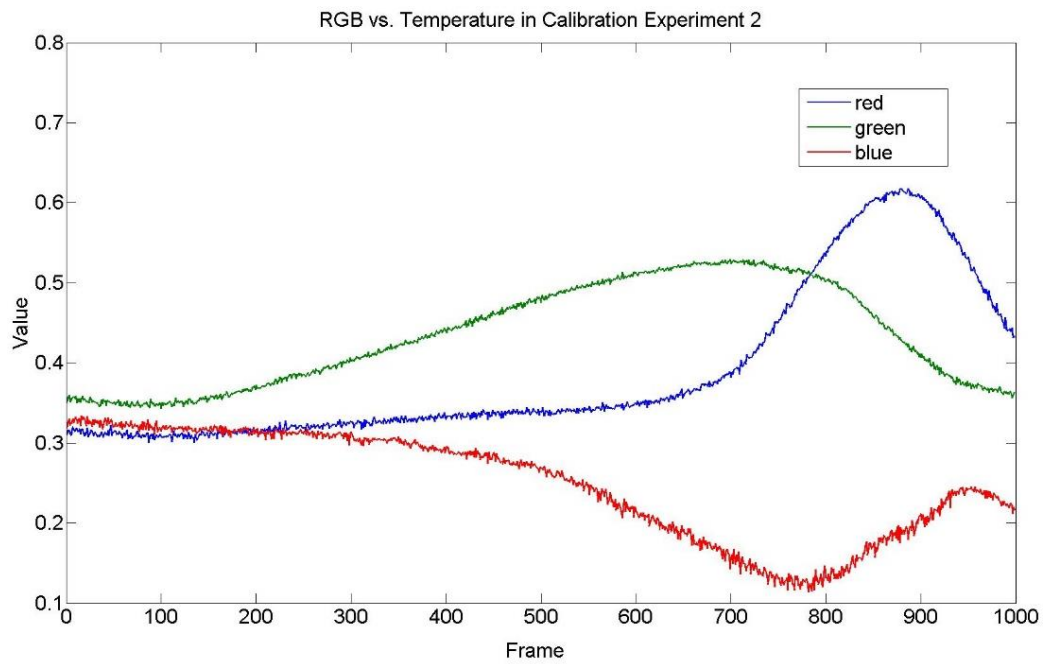


Figure 25 Temperature change in RGB color model

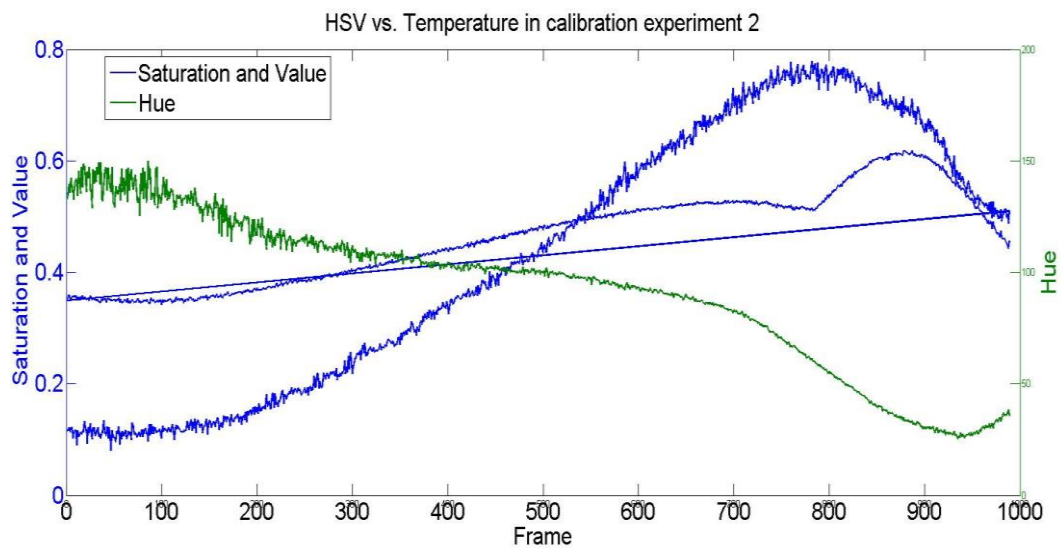


Figure 26 Temperature change in HSV model

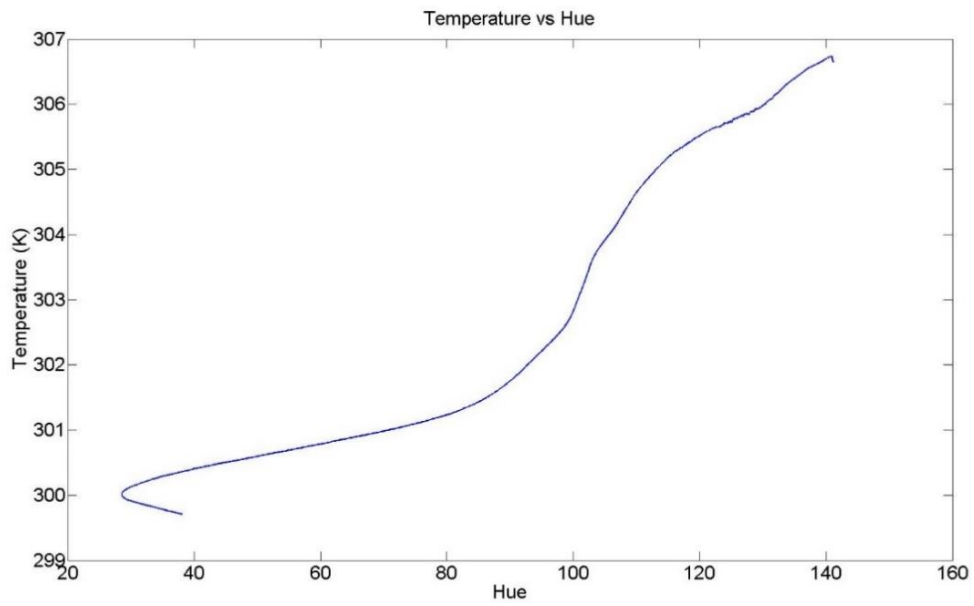


Figure 27 Temperature vs. hue relationship over the whole region without fitting

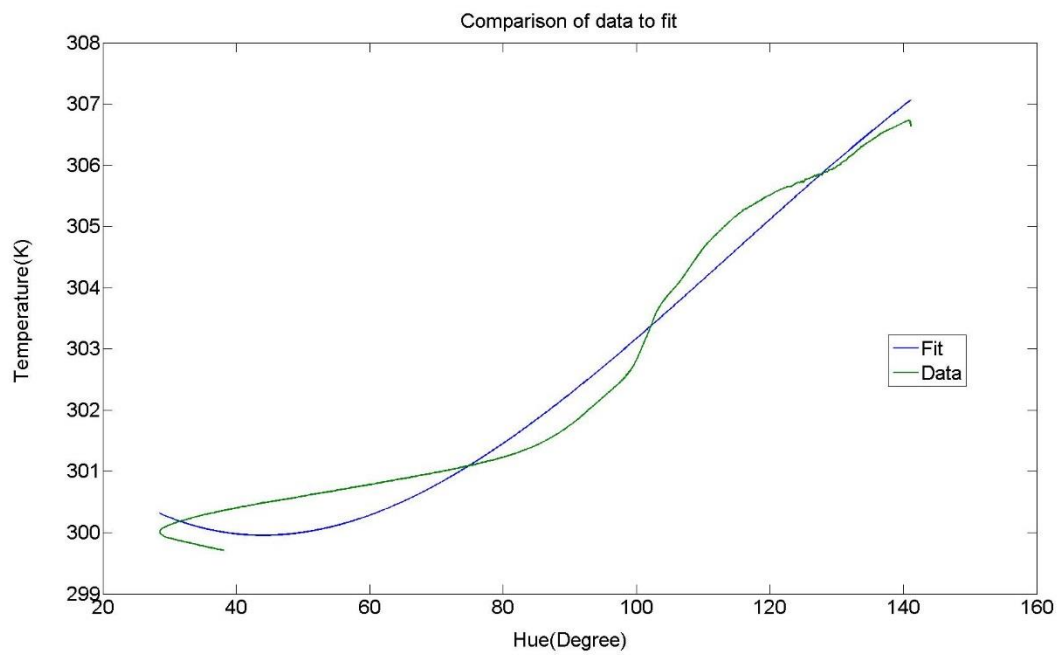


Figure 28 Temperature vs. hue over the whole region with fitting

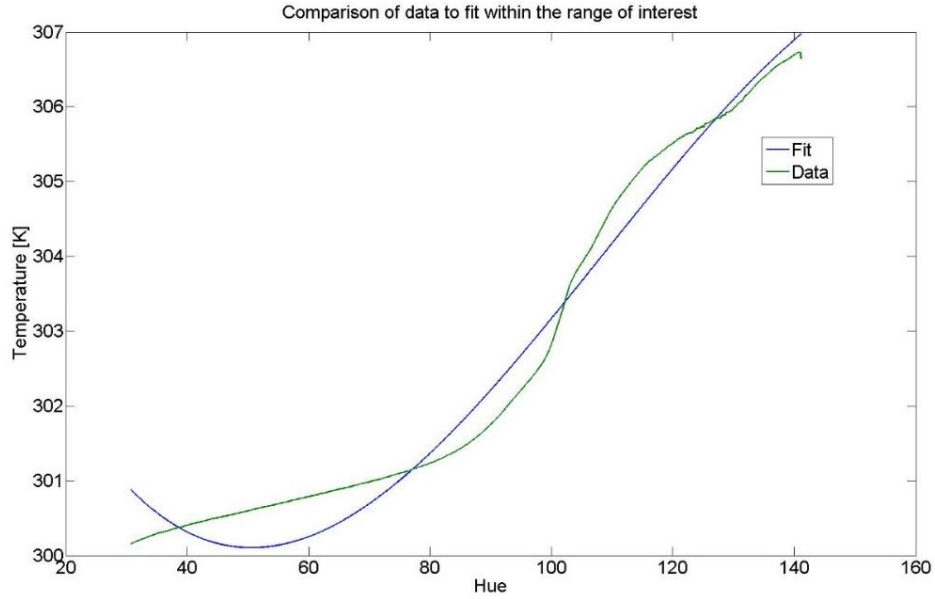


Figure 29 Temperature vs. hue curve fitting in 3rd order polynomial fitting for the interested region

4.2.3 Discussion

Over all, in Figure 27 hue increased as the temperature raised up and Figure 28 was the curve fitting for it. But in the beginning part of the plot, one hue value associate to two temperature values, that part is not the range the researcher interested in, so eliminate that portion. After eliminating, use the third order polynomial curve fitting and get result shown in Figure 29 . Even though there are still some deviations in the region of hue from 60 to 110, it is good enough for this third order polynomial curve fitting. For this fitting curve, the mathematical equation is $T = -0.015 \times 10^{-5} \times H^3 + 0.003298 \times H^2 - 0.2557 \times H + 305.9$ (10)

Where the T represents the temperature in Kelvin and H stands for Hue in degree.

4.3 reaction time measurement experiment

4.3.1 Images from reaction time measurement experiment

The experiment was repeated for 6 times and recorded 6 videos. But since some errors occurred in playing run 4 and run 6, so the researcher only processed data for run 1,2,3and 5. The Figure 30 show the color change over the air temperature change pattern over the process. Due to the air blowing direction, so the color reacted most quickly and significantly at the region which red boxed, so the points were picked inside this region on wires and two points on each wire as shown in Figure 31 .

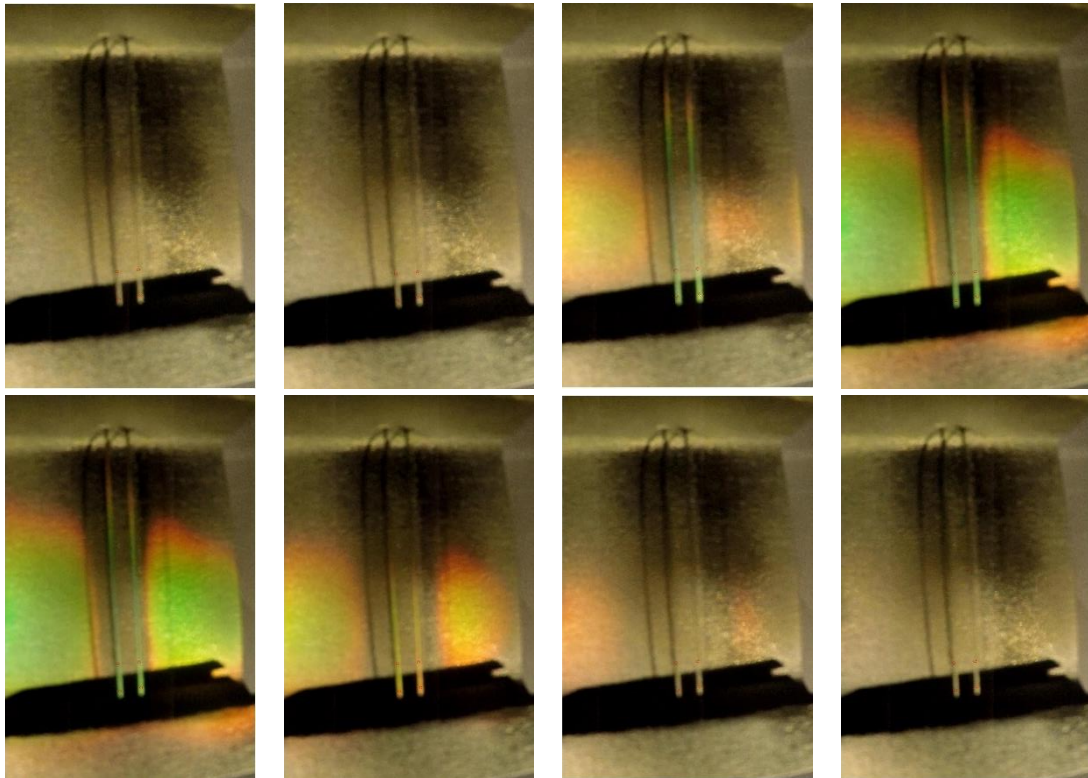


Figure 30 Reaction time measurement time results (above photos are taken every 1.3 seconds)

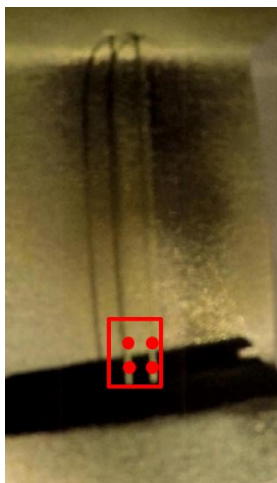


Figure 31 Points picking for data analysis

4.3.2 Data extrude from reaction time measurement experiments

Figure 32 below shows hue value changing over time, move the starting time at the same point for easier comparison. Since calibration experiment 2, the clear relationship between hue and temperature has been demonstrated, apply that equation to convert hue into temperature and got the plot in Figure 33 .

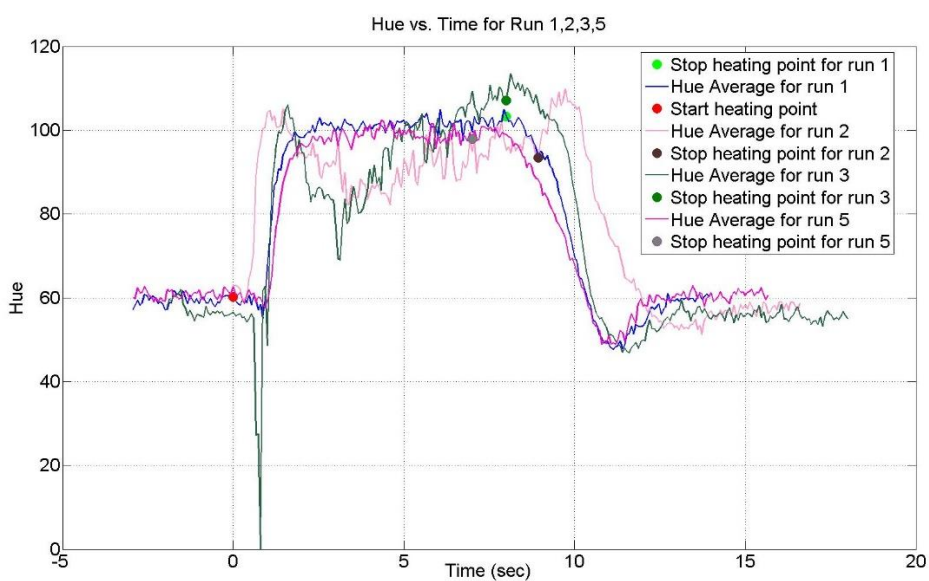


Figure 32 Hue change over time for the reaction time measurement experiments

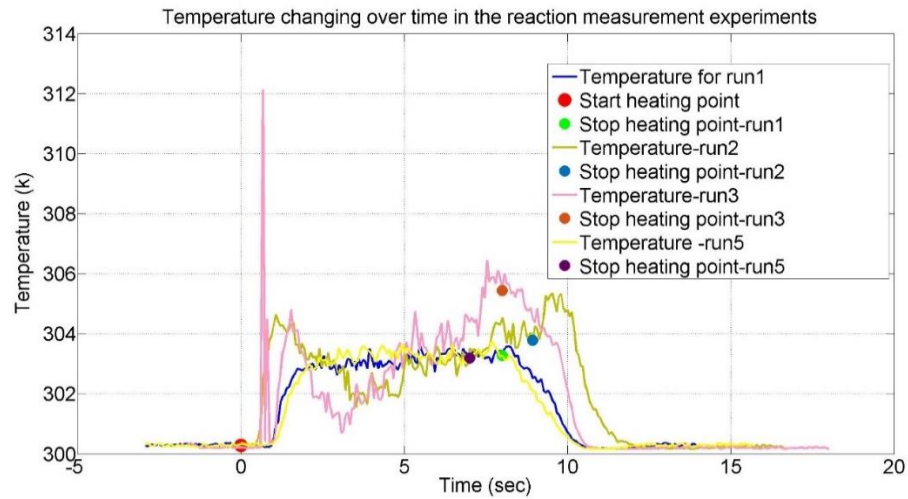


Figure 33 Temperature changing over time in reaction time measurement experiments

| Run | Heating up reaction Time(Sec) | Cooling down reaction Time(Sec) |
|------|-------------------------------|---------------------------------|
| 1 | 1.7667 | 3.1333 |
| 2 | 1.0000 | 4.2667 |
| 3 | 1.5333 | 3.4000 |
| 5 | 1.6667 | 3.9333 |
| Mean | 1.4917 | 3.6833 |

Table 1 Measured Reaction time

4.3.3 Discussion

From Figure 32 and Figure 33, run 3 has a suddenly increase in the beginning, that is because when put the heat gun to heat the wire up, it moved the whole structure including the camera. So the video lightness changed a lot and the hue value changed a lot as well as the temperature. Overall, run1 and run5 have the similar behavior, even though run 2 has a slightly difference with run1 and run5, run 2 and run 3 have similar

trend. From Table 1, the average reaction heating up time is about 1.49 seconds and average cooling down time is 3.68 seconds.

The average heating up time is shorter than average cooling down time is because when put the heat gun to blow constant air on the wires, it is a force convection and result in the heat transfer coefficient increasing. When working on cooling down process, there is few moving air around the wires so that the heat transfer coefficient is much lower and the process took a longer time [6].

Chapter 5 Conclusion and Future works

After completing all the experiments, a clear relationship between temperature and hue value has been demonstrated. This mathematical relationship can help to tell the temperature at wires for any random point by determining the color (hue) there. Besides, all the above experiments has proved that TLC is potentially a reliable temperature measurement technology for air temperature measurement.

For future study, following the experiment procedures for calibration experiment 2, replace the back paper with a no TLC applied one to get a clear version for observing the filaments color changing. Also, try to find some other materials for the filaments substitute for the fishing line for a quicker response. Furthermore, try to find a suitable material for the window to observe in the blowdown wind tunnel for TLC air temperature measurement.

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Appendix

Appendix A

Appendix A-1 Observing window drawing

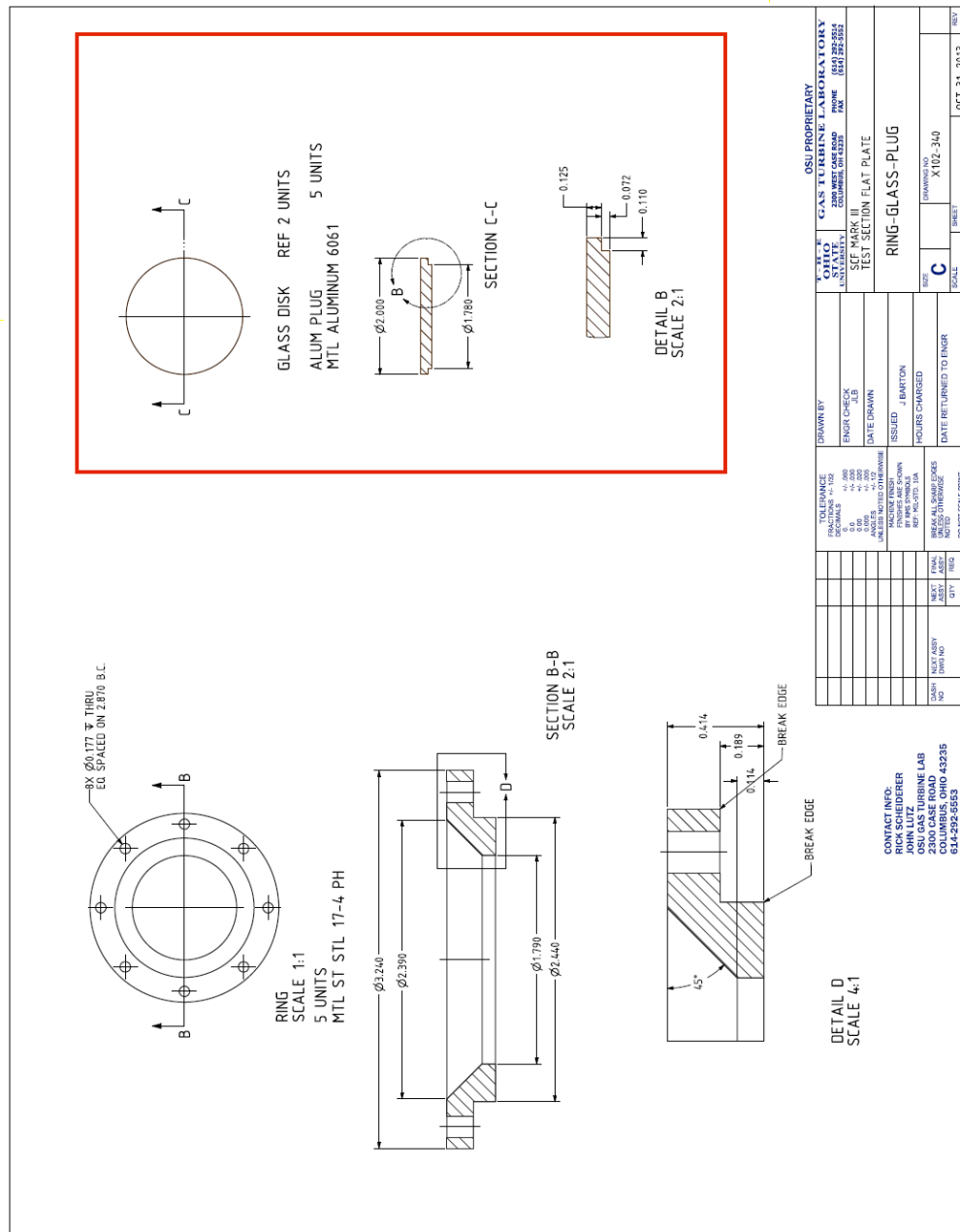


Figure A- 1 Window drawing

Appendix A-2 Test piece 2 design drawing

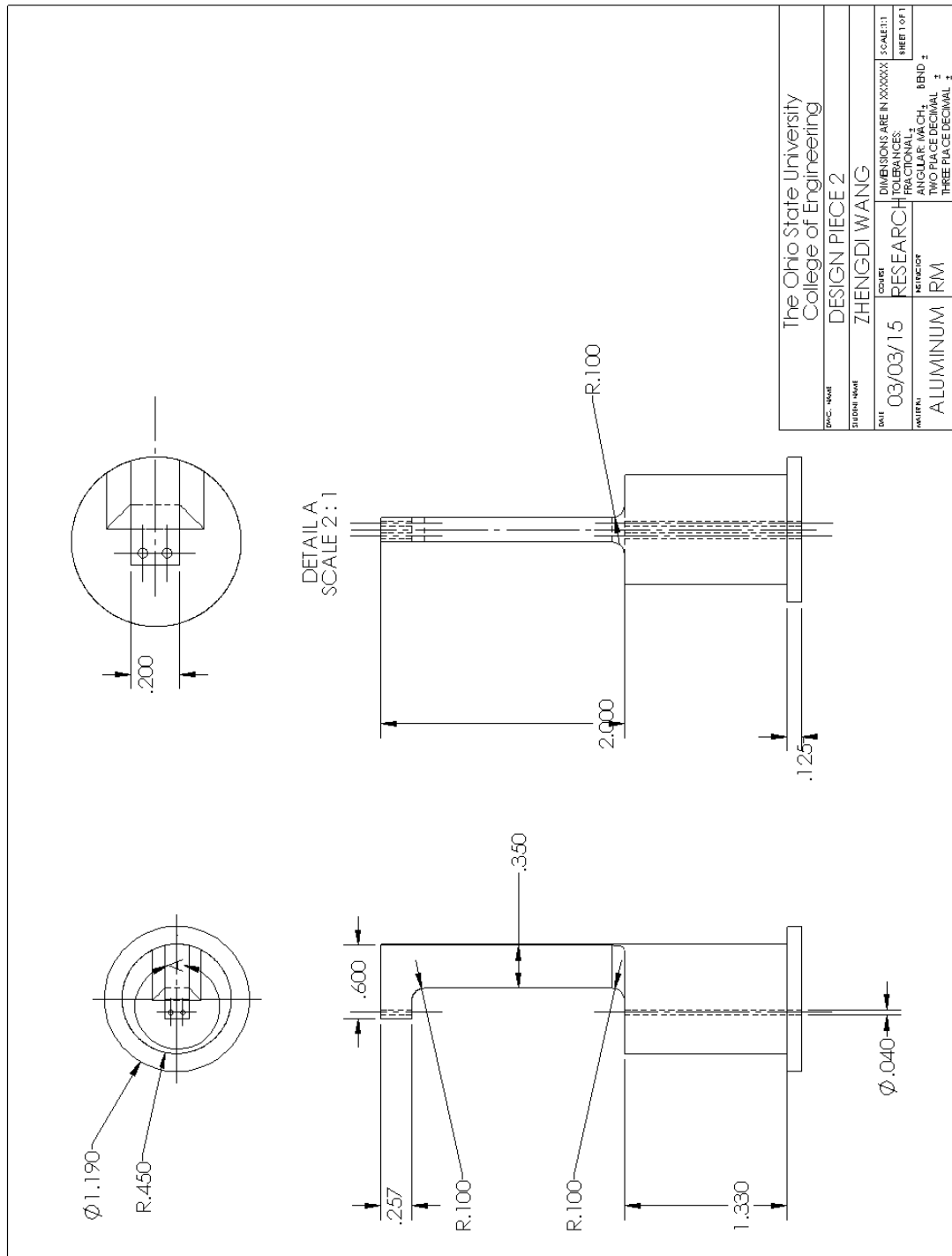


Figure A- 2 Test piece design 2

Appendix-B Callendar–Van Dusen Equation and RTD Temperature Sensors [12]

The correlation between the resistance and temperature of the RTD is described by the Callendar-Van Dusen equation.

For temperature: $-200^{\circ}\text{C} \leq t \leq 0^{\circ}\text{C}$,

$$R_T = R_0[1 + AT + BT^2 - (t - 100)CT^3] \quad (11)$$

$$R_0 = \text{Resistance at } 0^{\circ}\text{C}$$

$$T = \text{Temperature in } ^{\circ}\text{C}$$

Equation (1) is the complete version of the Callendar-Van Dusen equation. A, B and C are known as the Callendar-Van Dusen constants, defined by the following equations:

$$A = \alpha + \frac{\alpha\delta}{100}$$
$$B = \frac{-\alpha\delta}{100^2}$$
$$C = \frac{-\alpha\beta}{100^4}$$

α, β and δ are the constants that are found with the following equations:

$$\alpha = \frac{R_{100} - R_0}{100 + R_0}$$

$$\beta = \text{constant if } t < 0^{\circ}\text{C, else zero}$$

$$\delta = \frac{R_0[1 + \alpha(260)] - R_{200}}{4.16R_0\alpha}$$

Beta is found empirically and is constant at temperatures less than 0°C ; for temperatures greater than 0°C , beta is zero. As can be seen from the equation for C, if beta is found to be zero when temperatures are above 0°C then C is zero. When C is zero the complete version of the Callendar-Van Dusen equation can be simplified:

For Temperature: $0^{\circ}\text{C} \leq t \leq 661^{\circ}\text{C}$,

$$R_T = R_0[1 + AT + BT^2] \quad (12)$$

Equation (11) is typically used for temperatures below 0°C , whereas equation (12) is used for temperatures above 0°C . When equation (12) is used for temperatures below 0°C there is some error associated with the calculated resistance. Below -100°C the error is too significant to justify using equation (12) in place of equation (11).

The Callendar-Van Dusen equation that is detailed above is for platinum RTDs. RTDs come in various pure metals such as: platinum, nickel, and iron. Platinum is the most commonly used material for RTDs because of its wide temperature range, accuracy, stability and linearity. Platinum RTDs have positive temperature coefficients, meaning their resistance increases with increases in temperature. The typical sensitivity for platinum RTDs is $0.4\Omega/\text{C}$. Sensitivity is the change in resistance for every 1°C change in temperature. This low sensitivity is well suited for a RTDs' wide temperature range. When compared to other temperature sensitive devices, such as thermistors, RTDs have better performance. Thermistors can have positive or negative temperature coefficients. A typical $10\text{k}\Omega$ thermistor sensitivity is $-1699\Omega/\text{C}$ at 0°C . This higher sensitivity and the thermistors' smaller temperature range give the thermistor a non-linearity which is not favorable over wider temperature ranges.